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EFFECT OF FLAME STABILIZER DESIGN ON PERFORMANCE AND EXHAUST POLLUTANTS OF A TWO-ROW SWIRL-CAN COMBUSTOR OPERATED TO NEAR-STOICHIOMETRIC CONDITIONS

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16. Abstract

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EFFECT OF FLAME STABILIZER DESIGN ON PERFORMANCE AND EXHAUST POLLUTANTS OF A TWO-ROW SWIRL-CAN COMBUSTOR OPERATED TO NEAR-STOICHIOMETRIC CONDITIONS

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SUMMARY

Emissions and performance characteristics were determined for two full-annulus swirl-can modular combustors operated to near-stoichiometric fuel-air ratios. The tests were conducted to obtain stoichiometric data at inlet air temperatures from 756 to 894 K and to determine the effect of a flat-plate circular flame stabilizer with upstream fuel injection and a contraswirl shrouded flame stabilizer with downstream fuel injection. The contraswirl flame stabilizer did not produce any improvement in combustor performance or emissions over the simple flat-plate circular flame stabilizer. The flat-plate circular flame stabilizer reached a maximum average exit temperature of 2140 K with a combustion efficiency of 95.8 percent at a combustor inlet air temperature of 756 K. At the same exit and inlet air temperatures, the contraswirl flame stabilizer was 92 percent efficient. At a constant combustor inlet air temperature of 756 K, maximum oxides-of-nitrogen emissions indices occurred at a fuel-air ratio of 0.037 for the contraswirl flame stabilizer and 0.045 for the flat-plate circular design. The maximum oxides-of-nitrogen level recorded was 32.3 grams per kilogram of fuel for the contraswirl design at an inlet temperature of 894 K and a fuel-air ratio of 0.037. Measured emissions also included carbon monoxide and unburned hydrocarbons.

INTRODUCTION

An experimental test program was conducted to evaluate the effects of two swirl-can flame stabilizer designs on combustor performance and emissions of a combustor operated to near-stoichiometric fuel-air ratios. Measured emissions included oxides of nitrogen, carbon monoxide, and unburned hydrocarbons.

The swirl-can combustor has received considerable attention as a combustor design suitable for reducing oxides-of-nitrogen (NO_x) emissions. However, the primary application for swirl-can combustor technology has always been in engines requiring very high turbine-inlet air temperatures. Certain design features of the swirl-can combustor make it suitable for both applications:

(1) An array consisting of a large number of fuel injection/flameholder modules distributes combustion uniformly across the annulus.

(2) Quick mixing of burning gases and diluent air occurs because the swirl-can combustor passes nearly all airflow through the primary combustion zone and because large interfacial mixing areas exist between combustion gases and airflow around the swirl cans.

(3) Short combustor lengths and small recirculation zones for burning and mixing tend to limit NO_x formation. The short combustor lengths also reduce the required amount of liner cooling air. For high-temperature-rise applications, small liner cooling airflows are advantageous.

Swirl-can combustors have been investigated for several years at the NASA Lewis Research Center. Initial tests of a swirl-can combustor to near-stoichiometric fuel-air ratios are reported in reference 1. More recent studies (refs. 2 and 3) have included pollutant emissions measurements at stoichiometric conditions. However, near-stoichiometric operation in these previous studies was limited to inlet air temperatures of 589 K only. Three-row and two-row swirl-can combustor configurations were also tested during Phase 1 of the NASA Experimental Clean Combustor Program (refs. 4 and 5). Results of these tests and a two-row-design investigation (ref. 6) showed no significant difference in performance or emissions between the two- and three-row combustors operated to exit temperatures of 1500 K.

A more complete study of two- and three-row combustors operating to near-stoichiometric fuel-air ratios at inlet air temperatures to 894 K is reported in reference 7. Results of this study showed that the two-row combustor design produced substantially higher levels of carbon monoxide (CO) at fuel-air ratios greater than 0.040. The CO oxidation in these combustors appeared to be mixing limited. The difference in CO levels between the two combustors was in part due to flameholder design and the resultant mixing and higher surface-to-volume ratio of the two-row design.

This study expands the investigation of two-row swirl-can combustors operating to near-stoichiometric fuel-air ratios to include the effect on emissions of flame stabilizer design and resulting changes in combustor mixing. In particular, the best two-row combustor design of reference 8 is compared with the design used in reference 7. The nominal test conditions include combustor inlet air temperatures of 756, 839, and 894 K; reference velocities from 29 to 37 meters per second, an inlet total pressure of 6 atmospheres; and fuel-air ratios from 0.020 to 0.055. All tests used ASTM Jet-A fuel.

Measurements and calculations were made in the U.S. customary system of units. Values were converted to the SI system of units for this report.

APPARATUS

Combustor Design

The two combustors investigated in the program were two-row designs with 36 modules in each row (fig. 1). Each module consisted of a carburetor, a cone swirler, and a flame stabilizer (fig. 2). The two combustors differed in method and location of fuel entry, swirler design, and flame stabilizer geometry. The flat-plate circular flame stabilizer (model I, fig. 3) was designed so that its fuel impacted the center of the cone swirler. The contraswirl design (model II, fig. 4) had its fuel injected downstream of the swirler so that it impacted the upstream face of the circular disk that was mounted from the swirler face. Table I summarizes the differences between the two designs.

Model I was chosen as the baseline combustor because of the extensive work conducted on it and similar designs in references 6 to 8. Model II was selected for comparison because the single and cluster module evaluations of references 9 and 10 showed contraswirl and downstream fuel injection to improve mixing and reduce NO_x formation over solid flame stabilizer designs. The triangular blockage tabs of model II were added when a full-annular version (ref. 8) showed high levels of NO_x due to poor mixing as a result of low total combustor pressure loss. Hence, the blockage tabs were added to increase the airflow through the swirlers, improve mixing, and reduce NO_x formation through lower local equivalence ratios.

Test Facility

The annular swirl-can combustors were evaluated in a connected-duct test facility. A diagram of the facility and a sketch of the installation are shown in reference 6. Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section. Airflow rates were measured with an air orifice installed in accordance with ASME specifications. The test facility is described more completely in reference 11.

Instrumentation

For average combustor exit temperatures below 1700 K, combustor exit total pressures and temperatures were measured in the exit plane at 39 circumferential increments by three equally spaced, five-point, rotatable probes. At higher exit temperatures, these rakes were removed and three five-point, fixed-position, total-pressure rakes were installed.

Concentration measurements of nitric oxide, total oxides of nitrogen, carbon monoxide, unburned hydrocarbons, oxygen, and carbon dioxide were made with an on-line sampling system. The samples were drawn at the combustor exit plane by means of three equally spaced (circumferentially), five-point, radially averaged, water-cooled rotatable probes. The three probes were manifolded to a single sampling line and provided a 39-point survey of the exit. A total survey of the combustor exit required approximately 7 minutes.

Gas Sampling System

The gas sampling line and exhaust-gas analysis system are shown in figures 5 and 6. The sampling line was steam heated to 420 K. Sampling-line pressure was maintained at 6.9 N/cm^2 in order to supply sufficient pressure to operate the instruments. Sufficient sample is vented at the instruments to provide a line residence time of about 2 seconds.

The exhaust-gas analysis system is a packaged unit consisting of five commercially available instruments along with associated peripheral equipment necessary for sample conditioning and instrument calibration. In addition to visual readout, electrical inputs are provided to an IBM 360/67 computer for on-line analysis and evaluation of data.

The hydrocarbon content of the exhaust gas is determined by a Beckman Instruments model 402 hydrocarbon analyzer. This instrument is a flame ionization detector. The polarographic oxygen analyzer is a Beckman Instruments model 778.

The NO_x concentration is determined by a Thermo Electron Corporation model 10A chemiluminescent analyzer. The instrument includes a thermal reactor to reduce NO_2 to NO and was operated at 973 K. Both carbon monoxide (CO) and carbon dioxide (CO_2) analyzers are of the nondispersive infrared (NDIR) type (Beckman Instruments model 315B).

Gas Sampling Procedure

All analyzers were checked for zero and span prior to each test run and rechecked between data points. Solenoid switching within the console allows rapid selection of zero, span, or sample modes. Therefore, it was possible to check calibration accuracy frequently without disrupting testing.

Carbon monoxide and carbon dioxide emissions were corrected for the presence of water vapor. The correction included both inlet air humidity, which was nominally 0.003 kilogram of water per kilogram of air, and water vapor from combustion.

In order to check the sample validity, a fuel-air ratio based on the measured carbon concentrations was compared with metered fuel and airflow measurements. The carbon-based fuel-air ratios were within 95 to 110 percent of the metered values. For most test runs the carbon-based values were higher than the metered values. This is to be expected, as the gas sampling system does not completely cover the exit radial height and, thus, excludes some liner cooling air. The fuel-air ratios obtained from the fuel and airflow measurements were used in the computation of all emission indices and are the fuel-air ratios given on all data plots.

The combustor equilibrium temperature rise was computed by using the equilibrium program described in reference 12. A modified version of this program was also used to compute a temperature rise that corresponded with exit emissions measurements. For this purpose, the actual combustion process was assumed to be a constant-enthalpy, constant-pressure process. A tagged portion of the carbon in the system was allowed to react only to CO, the remainder to react normally. By increasing the tagged portion of the carbon, it was possible to force the equilibrium program to consider a "frozen equilibrium" composition whose CO content was greater than would be predicted by equilibrium considerations alone. An iteration was performed until the total CO in the system agreed with the experimental measurement. The temperature computed for this composition was assumed to be the average combustor exit temperature. Combustion efficiency was then computed as the ratio of this computed average temperature rise to the equilibrium temperature rise.

The work of references 1 to 3 relied on a choked nozzle as the primary means to determine exit temperature and combustion efficiency. Although combustion efficiency could also be inferred from the emissions measurements of the previous studies, the results were somewhat restricted as samples were obtained at a single circumferential location. Because the emissions results presented for this study were obtained with a rotatable sampling system, combustion exit temperature and combustion efficiency calculated from the measured emissions can be considered to be representative of average exit conditions. This approach eliminated the need for the choked nozzle and its associated operational difficulties.

RESULTS AND DISCUSSION

The baseline combustor (model I) was tested to provide emissions and performance data for comparison with the advanced contraswirler combustor design. Data were obtained with thermocouples installed in the exhaust duct to fuel-air ratios of 0.026 at inlet air temperatures of 756 to 894 K. For testing at higher fuel-air ratios, the thermocouples were removed. Data were obtained with on-line gas analysis, where the intent was to test to fuel-air ratios approaching the stoichiometric value. Unfortunately, an internal fuel line broke during tests at 756 K and the combustor was severely damaged. Therefore, the remainder of the test program was conducted with the model II combustor. However, sufficient data do exist to draw some comparisons and conclusions as to the effectiveness of the two flame stabilizer designs.

Unburned Hydrocarbons

The emission indices for unburned hydrocarbons as well as all other data for both designs are listed in table II. In all cases, hydrocarbon emission indices were less than 0.62 gram per kilogram of fuel for both combustors.

Carbon Monoxide

Carbon monoxide emissions as a function of fuel-air ratio are shown in figure 7. The overall levels are extremely high as compared with combustors operating at conventional exit temperatures. At the highest fuel-air ratios, the CO emission indices for the shrouded contraswirl design were 420 to 520 grams per kilogram of fuel depending on the combustor inlet air temperature. The CO emission levels for the flat-plate circular flame stabilizer design are shown only for the higher fuel-air ratios at 756 K inlet air temperature. These emission levels were 38 percent less than those of the contraswirl design operated at the same combustor inlet air temperature and a fuel-air ratio of 0.045.

Shown for comparison in figure 7 are CO levels predicted for a theoretical equilibrium composition of the exhaust gas. These levels were computed by using the method of reference 12. They established the practical lower limit for CO emissions at the combustor exit and are not indicative of inefficient operation. However, levels of CO greater than the equilibrium level do indicate inefficient operation. At a given fuel-air ratio an increase in the exhaust-gas temperature causes an increase in the

level of equilibrium CO. The actual combustor CO emissions decrease with increasing inlet air temperature, indicating an increase in combustion efficiency.

Oxides of Nitrogen

Measured emission indices for NO_x are shown in figure 8. The most striking feature of the curves is the difference between the rate of change of NO_x for the two models at 756 K inlet air temperature. The contraswirl design was tested to a maximum fuel-air ratio of 0.055 and shows a fairly steep rise in NO_x emissions, with a peak value occurring at approximately 0.038 fuel-air ratio. The flat-plate circular flame stabilizer shows a more moderate rise in NO_x emissions, which were still increasing with fuel-air ratio to the maximum tested value of 0.045.

Combustion Efficiency and Average Exhaust-Gas Temperature

The combustion efficiency was determined by taking the ratio of the temperature rise evaluated from emissions measurements to the equilibrium temperature rise. The results are shown in figure 9. Combustion efficiency for the two models at all inlet air temperatures was greater than 99 percent for fuel-air ratios to 0.034. For higher fuel-air ratios, particularly above 0.040, where the CO level increases rapidly, efficiency falls off and shows a slight dependency on inlet air temperature. As an example, for the shrouded contraswirl design at 0.054 fuel-air ratio, combustion efficiency increased from 90.3 to 92.2 percent as the inlet air temperature was increased from 756 to 894 K.

The combustor efficiency is shown as a function of the calculated average combustor exit temperature in figure 10. At an inlet air temperature of 894 K, the shrouded contraswirl design achieved the highest sustained average exit temperature recorded in the test program, 2315 K, and an efficiency of 92 percent. The flat-plate circular design achieved an exit temperature of 2140 K and an efficiency of 95.8 percent at an inlet air temperature of 756 K.

Comparison of Combustors

The combustors can only be effectively compared by using the data obtained at 756 K over the fuel-air ratio range from 0.02 to 0.055. The major differences are in the generally lower combustion efficiencies and the higher NO_x emissions of model II

relative to model I. As stated previously, the purpose of the contraswirl flame stabilizer design was to force more air into the module wake and to mix and dilute the combustion zone as quickly as possible. Thus, model II had the normally open areas between modules partially closed by blockage plates to force air through the swirlers. This had not been done to a similar combustor reported in reference 8, with the result that only low airflows passed through the contraswirl flame stabilizer and poor performance was obtained. This added blockage in model II significantly decreased the open flow area of this design from that of model I. The combustors were, therefore, tested at operating conditions where the total-pressure loss was held constant. This means that the reference velocities (table II) of model I were approximately 10 percent greater than those of model II. In spite of the lower reference velocities, the model II combustor had lower combustion efficiencies at high fuel-air ratios. The difference in efficiency is attributable to increases in the CO emission index (fig. 7) rather than to increases in hydrocarbons. Therefore, the differences in combustion efficiency for the two models are not attributable to the manner of fuel injection but rather to the mixing processes occurring in the module wake as related to the flame stabilizer design.

The NO_x emissions of the two combustors cannot be directly compared, as shown in figure 8, because of differences in reference velocity. These emissions have been compared in figure 11, which uses the correlating parameter of reference 8

$$\frac{P^{1/2} e^{T_{in}/288} T_{exit}}{V_{ref}}$$

where

- P inlet total pressure
- T_{in} inlet air temperature
- T_{exit} exit temperature
- V_{ref} reference velocity

to account for differences in the reference velocity. Two points are obvious from the figure. First, the NO_x emissions of model II are significantly greater than those of model I at comparable high-exit-temperature conditions. Secondly, the maximum NO_x emissions probably occur at a lower exhaust temperature (or fuel-air ratio as shown in fig. 8) for model II than for model I. Similar effects have been observed in reference 7, where differences in module swirler airflow rate were responsible for shifting the peak of NO_x emissions to different fuel-air ratios. While the peak NO_x emission of

model I was not actually determined, this peak probably occurs at higher fuel-air ratios than the peak NO_x emission of model II. This indicates that forcing more air through the swirlers of model II did not increase mixing. Had mixing been improved, the maximum value of NO_x would have occurred at higher overall fuel-air ratios and, in addition, the NO_x emission index should have been lower than that for model I. One can only conclude that the contraswirl design did not produce the desired effect in the module wake region. The simpler flame stabilizer design of model I demonstrated a high degree of mixing between combustion gases in the module wake and air flowing over the flame stabilizer. This is confirmed by the low NO_x emission indices, the higher fuel-air ratio at the maximum NO_x index, and the lower CO emissions.

Why the emissions performance of model II was so poor relative to model I can only be explained by the fact that the contraswirl design did not achieve the level of mixing that was expected of it.

SUMMARY OF RESULTS

Emissions and performance characteristics were determined for two swirl-can flame stabilizer designs in a full-annulus combustor operated to near-stoichiometric fuel-air ratios. The emissions measured were oxides of nitrogen, carbon monoxide, and unburned hydrocarbons. Test conditions included combustor inlet air temperatures of 756, 839, and 894 K; reference velocities from 30 to 39 meters per second; an inlet total pressure of 6 atmospheres; and fuel-air ratios varying from 0.020 to 0.055. The following results were obtained:

1. Downstream fuel injection produced no improvement in fuel atomization or distribution over upstream fuel injectors, as shown by the low emissions index of unburned hydrocarbons, which was less than 0.50 for both designs.

2. Using high blockage and a contraswirl flame stabilizer to increase mixing and to provide more primary airflow did not lower the oxides-of-nitrogen emission levels from those obtained with a simple, flat-plate circular flame stabilizer.

3. At a constant inlet air temperature of 756 K, maximum oxides-of-nitrogen emission levels for the flat-plate circular flame stabilizer had not peaked at its highest fuel-air ratio of 0.045. Maximum oxides-of-nitrogen emission levels for the contraswirl design peaked at a nominal fuel-air ratio of 0.037 at all three inlet air temperatures.

4. Maximum exit temperature achieved was 2140 K for the flat-plate circular flame stabilizer design at an inlet air temperature of 756 K. For the contraswirl

design, the maximum exit temperature was 2315 K at an inlet air temperature of 898 K.

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TABLE I. - SUMMARY OF DIFFERENCES IN THE TWO FLAME STABILIZER DESIGNS

[Liner cooling, 11 percent of total cooling.]

Model	Type of flame stabilizer	Fuel injection	Swirler-flow area, cm^2	Blockage, percent
I	Flat-plate circular	Upstream of swirler	2.71	67.8
II	Circular contraswirl	Downstream of swirler	[a]5.61	75

[a]Includes the 2.9-cm^2 flow area of the contraswirl.

TABLE II. - PERFORMANCE AND EMISSION DATA FOR 72-SWIRL-CAN COMBUSTORS

(a) Flat-plate circular flame stabilizer (model I)

Total inlet pressure, N/cm^2	Average combustor inlet air temperature, K	Inlet airflow rate, kg/sec	Diffuser inlet Mach number, M_3	Reference velocity, m/sec	Measured fuel-air ratio, $(f/a)_m$	Combustor exit temperature, K	Pattern factor, δ	Combustor pressure loss, $\frac{\Delta P}{P} \times 100$, percent	Thermocouple efficiency, percent	Emission levels of - Oxides of nitrogen, ppm	Oxides of nitrogen, $\frac{g\ NO_x}{kg\ fuel}$	Unburned hydrocarbons, ppm	Unburned hydrocarbons, $\frac{g\ HC}{kg\ fuel}$	Carbon monoxide, ppm	Carbon monoxide, $\frac{g\ CO}{kg\ fuel}$	Carbon dioxide, ppm	Carbon dioxide, $\frac{g\ CO_2}{kg\ fuel}$	Gas analysis efficiency, η_{gs}, percent	Fuel-air ratio ratio, $\frac{(f/a)_{gs}}{(f/a)_m}$
62.4	757	38.2	0.21	33.3	0.0152	1291	0.39	6.97	97.11	72.6	7.7	9.5	0.30	188.9	12.2	30 266	3080	99.75	0.981
62.4	759	38.2		33.5	.0183	1393	.37	6.95	97.23	98.1	8.7	3.3	.09	103.6	5.6	36 426	3096	99.94	.983
62.2	760	38.3		33.6	.0212	1448	.36	7.20	97.25	122.2	9.4	1.5	.03	70.5	3.3	42 222	3104	99.93	.984
62.5	758	38.1		33.3	.0243	1575	.34	6.95	96.99	152.3	10.2	.9	.02	69.8	2.9	50 689	3095	99.92	.981
62.5	756	37.9		33.0	.0263	1637	.38	7.03	97.4	165.3	10.3	1.2	.02	106.7	4.0	51 858	8081	99.91	.977
62.7	761	38.4	.23	33.4	.0221	1515	----	7.32	-----	119.6	8.8	1.32	.03	70.9	3.2	44 841	3115	99.92	1.00
62.2	759	38.6	.23	33.7	.0259	1635	----	7.50	-----	158.9	10.0	1.05	.02	93.2	3.6	52 924	3188	99.92	
62.5	758	38.6	.23	33.6	.0299	1743	----	7.43	-----	210.4	11.5	.83	.01	197.3	6.6	60 433	3164	99.84	
62.5	760	38.6	.22	33.7	.0357	1905	----	7.50	-----	276.2	12.7	1.09	.01	965.9	27.1	71 287	3140	99.36	
62.5	760	38.5	.22	33.6	.0417	2046	----	7.54	-----	352.6	13.9	5.13	.06	304.4	73.5	80 656	3060	98.27	1.01
62.5	761	38.6	.21	33.7	.0454	2140	----	7.62	-----	391.2	14.3	13.91	.15	312.1	180.9	85 460	2991	95.75	1.04
62.1	842	37.9	.22	36.9	.0171	1426	.45	7.67	97.86	115.8	11.0	1.7	.05	66.9	3.9	33 588	3056	99.90	.969
61.9	842	37.9	.22	37.1	.0213	1556	.42	7.83	97.56	157.3	12.1	1.2	.03	49.8	2.3	41 910	3072	99.93	.973
62.1	841	38.09	.22	37.1	.0243	1646	.39	7.9	97.68	191.6	12.9	1.3	.03	56.4	2.1	47 977	3081	99.93	.976
61.7	840	38.2	.23	37.4	.0164	1371	.43	7.7	98.84	102.1	10.8	3.4	.11	51.9	3.3	30 461	3074	99.92	.934
62.2	899	37.8	.23	39.3	.0155	1428	.42	7.9	98.8	125.9	13.1	1.8	.06	59.3	3.4	30 692	3064	99.91	.971
61.8	898	38.0		39.8	.0179	1501	.43	8.2	98.4	150.8	13.7	1.6	.04	54.6	3.0	35 508	3084	99.90	.977
61.7	898	38.1		39.9	.0211	1599	.43	8.3	98.0	187.7	14.5	1.7	.04	54.6	2.6	41 846	3087	99.90	.978
62.0	898	37.9		39.6	.0239	1680	.39	8.1	97.6	226.7	15.5	1.7	.03	53.3	2.2	47 093	3080	99.90	.975
62.0	757	33.3	.19	29.2	.0200	1493	----	7.39	-----	120.1	9.52	12.1	.29	149.0	7.2	43 661	3310	99.8	1.053
62.2	761	33.0	.19	29.0	.0244	1630	----	7.20	-----	172.9	11.51	5.1	.10	166.3	6.74	52 496	3344	99.83	1.063
62.4	758	33.4		29.1	.0275	1729	----	7.15	-----	256.5	15.24	4.5	.08	283.5	10.2	59 318	3370	99.75	1.074
62.0	760	32.9		29.0	.0327	1867	----	7.22	-----	382.5	19.19	3.06	.05	1 041.3	31.81	68 596	3292	99.25	1.060
62.2	758	33.1		28.9	.0365	1963	----	7.25	-----	489.8	22.12	4.14	.06	2 291.4	63.00	75 598	3266	98.52	1.069
61.8	759	33.3	.20	29.4	.0403	2067	----	8.00	-----	521.5	21.41	3.20	.04	6 134.7	153.36	80 612	3166	96.40	1.085

(b) Contraswirl flame stabilizer (model II)

Total inlet pressure, N/cm^2	Average combustor inlet air temperature, K	Inlet airflow rate, kg/sec	Diffuser inlet Mach number, M_3	Reference velocity, m/sec	Measured fuel-air ratio, $(f/a)_m$	Combustor exit temperature, K	Pattern factor, δ	Combustor pressure loss, $\frac{\Delta P}{P} \times 100$, percent	Thermocouple efficiency, percent	Oxides of nitrogen, ppm	Oxides of nitrogen, $\frac{g\ NO_x}{kg\ fuel}$	Unburned hydrocarbons, ppm	Unburned hydrocarbons, $\frac{g\ HC}{kg\ fuel}$	Carbon monoxide, ppm	Carbon monoxide, $\frac{g\ CO}{kg\ fuel}$	Carbon dioxide, ppm	Carbon dioxide, $\frac{g\ CO_2}{kg\ fuel}$	Gas analysis efficiency, η_{gs}, percent	Fuel-air ratio ratio, $\frac{(f/a)_{gs}}{(f/a)_m}$
62.0	758	33.3	0.19	29.2	0.0445	2131	----	7.68	-----	492.5	18.37	5.65	0.060	11 208	254.6	82 738	2953	94.03	1.070
62.2	760	33.2	.19	29.1	.0487	2186	----	7.49	-----	468.9	16.03	11.69	.120	17 076	356.0	83 712	2742	91.65	1.057
62.3	757	33.1	.19	28.9	.0550	2261	----	7.38	-----	424.6	12.98	47.05	.430	27 932	519.8	83 753	2449	87.78	1.051
62.8	845	32.8	.20	31.7	.0288	1803	----	7.24	-----	415.4	23.59	1.22	.620	284.3	9.8	59 621	3239	99.77	1.031
62.1	844	33.1	.20	32.3	.0344	1960	----	7.46	-----	580.9	27.75	.84	.012	1 463	42.5	70 429	3219	99.00	1.042
62.5	843	33.0	.20	32.0	.0408	2106	----	7.38	-----	667.9	27.11	1.198	.015	6 457	159.5	78 717	3056	96.26	1.052
62.3	842	33.1	.20	32.2	.0447	2183	----	7.51	-----	658.8	24.49	4.23	.050	11 424	258.5	82 046	2917	93.94	1.061
62.3	841	32.0	.19	30.9	.0251	1709	----	7.10	-----	281.1	18.25	3.39	.066	141.4	5.59	53.443	3319	99.86	1.054
62.3	846	32.0	.20	31.2	.0303	1855	----	7.58	-----	447.9	24.16	2.93	.047	410.8	13.49	63 163	3259	99.68	1.039
61.8	841	32.2	.21	31.5	.0482	2249	----	7.42	-----	613.7	21.23	9.17	.085	15 618	328.92	85 038	2814	92.29	1.065
62.3	844	31.9	.10	31.0	.0551	2299	----	7.35	-----	556.6	17.02	34.68	.321	26 090	485.6	83 042	2429	88.59	1.025
62.6	840	31.9	.20	30.8	.0409	2114	----	7.06	-----	627.9	25.37	2.00	.024	73 449	180.7	78 945	3052	95.76	1.062
62.5	900	32.1	.20	33.1	.0243	1714	----	6.90	-----	308.9	20.66	.75	.015	124.9	5.1	50 416	3225	99.88	1.024
62.2	898	32 2	.21	33.4	.0283	1834	----	7.60	----	453.7	26.22	.82	.014	571.7	20.1	58 685	3244	99.53	1.038
61.8	899	32 1	.20	33.5	.0324	1934	----	7.37	-----	574.7	29.10	.92	.014	1 200.9	37.9	65 537	3174	99.13	1.024
62.5	899	32.0	.20	33.0	.0379	2045	----	7.35	-----	725.4	32.34	1.01	.014	3 053.5	82.9	72 907	3109	98.06	1.028
62.6	899	31.9	.20	32.9	.0409	2126	----	7.56	-----	745.3	30.15	1.47	.018	7 314.8	180.1	76 824	2973	95.78	1.035
62.5	898	32.0	.21	32.9	.0450	2206	----	7.45	-----	761.7	28.12	3.36	.037	11 569	260.9	80 630	2848	93.91	1.038
62.2	896	32.1	.20	33.2	.0486	2242	----	7.18	-----	696.5	23.93	8.65	.090	15 625	326.9	81 382	2675	92.33	1.018
61.8	897	32.3	.20	33.6	.0526	2303	----	7.51	-----	652.1	20.79	23.89	.23	21 850	424.0	82 744	2523	90.05	1.022
62.0	898	32.2	.21	33.5	.0548	2315	----	7.99	-----	635.9	19.53	41.67	.39	25 837	468.2	81 881	2406	88.99	1.007

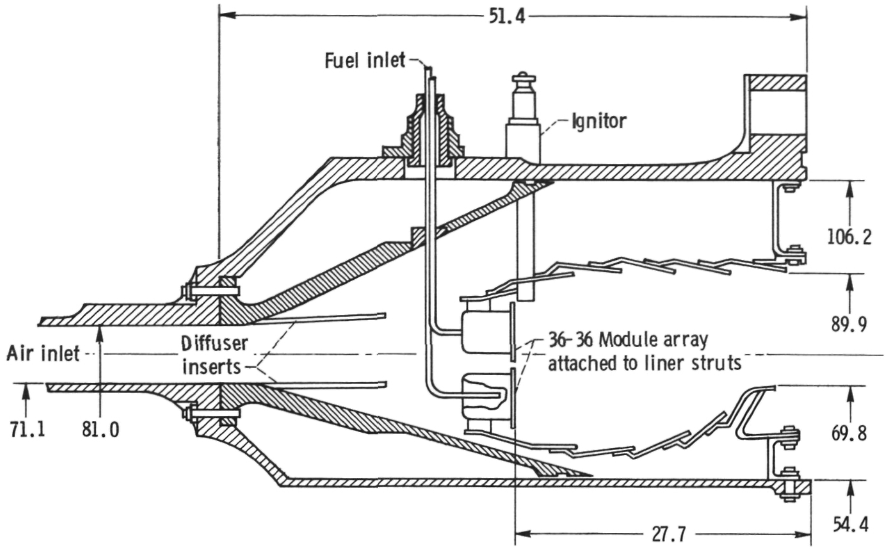

Figure 1. - Full-annular high-temperature combustor having two rows of swirl cans (72). (Dimensions are in cm.)

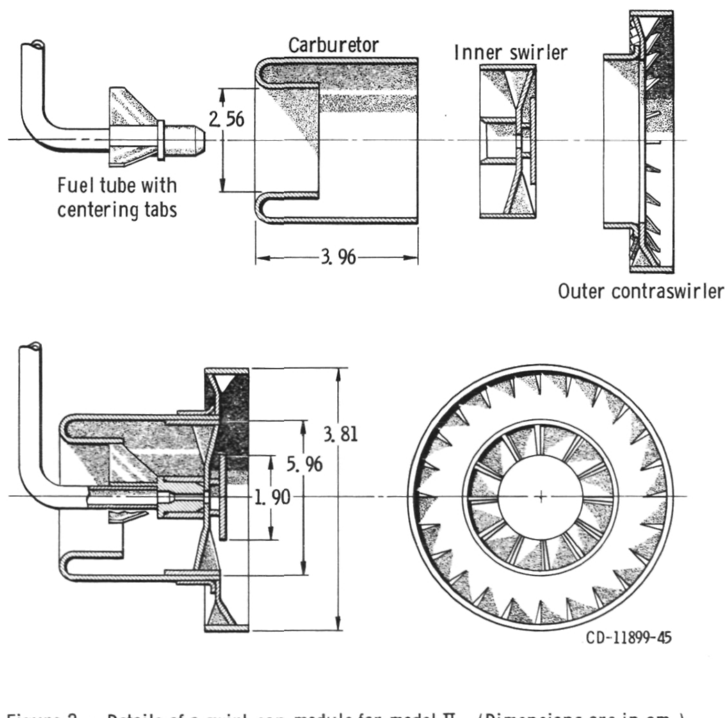

Figure 2. - Details of a swirl-can module for model II. (Dimensions are in cm.)

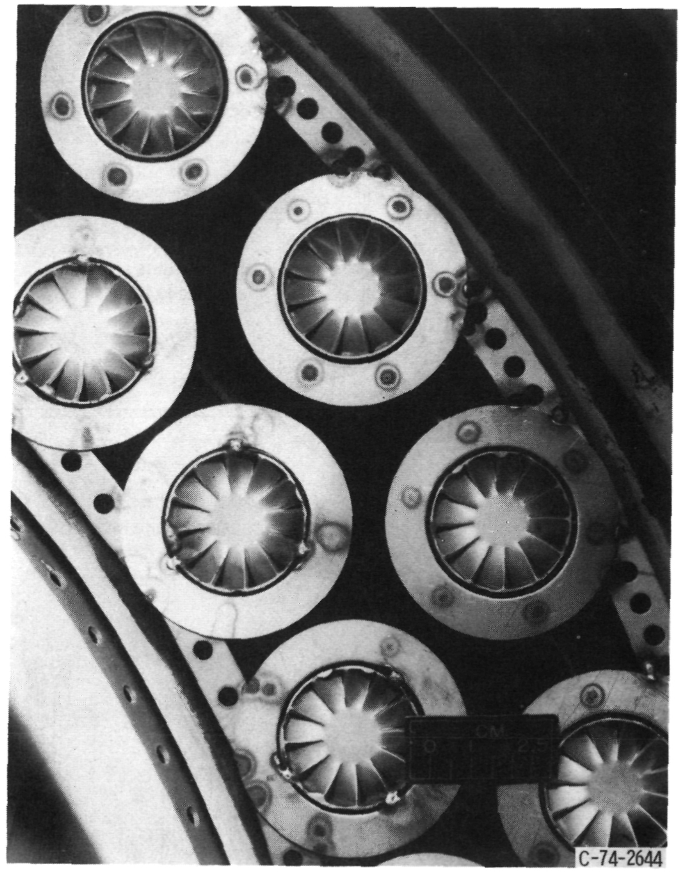

Figure 3. - Sector view of flat-plate circular flame stabilizer (model I) module array.

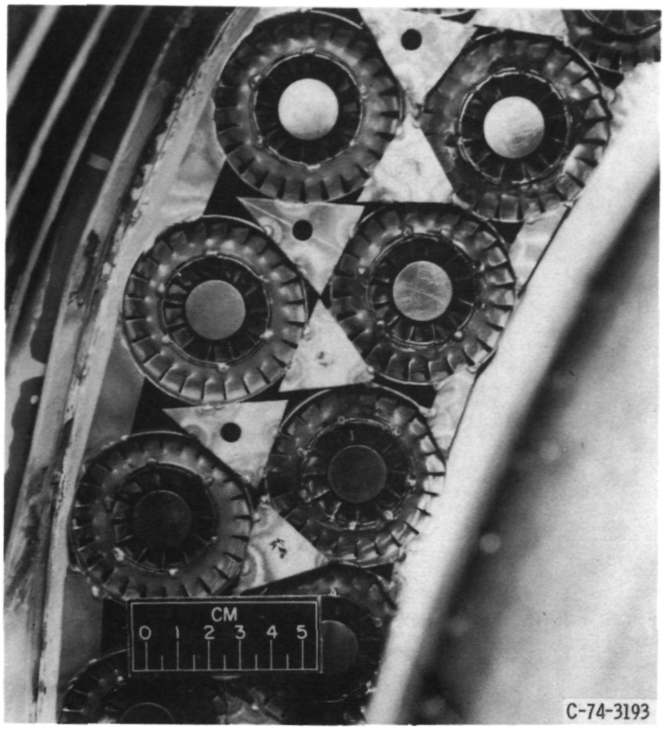

Figure 4. - Sector view of contraswirl combustor (model II) module array showing contraswirls and blockage tabs.

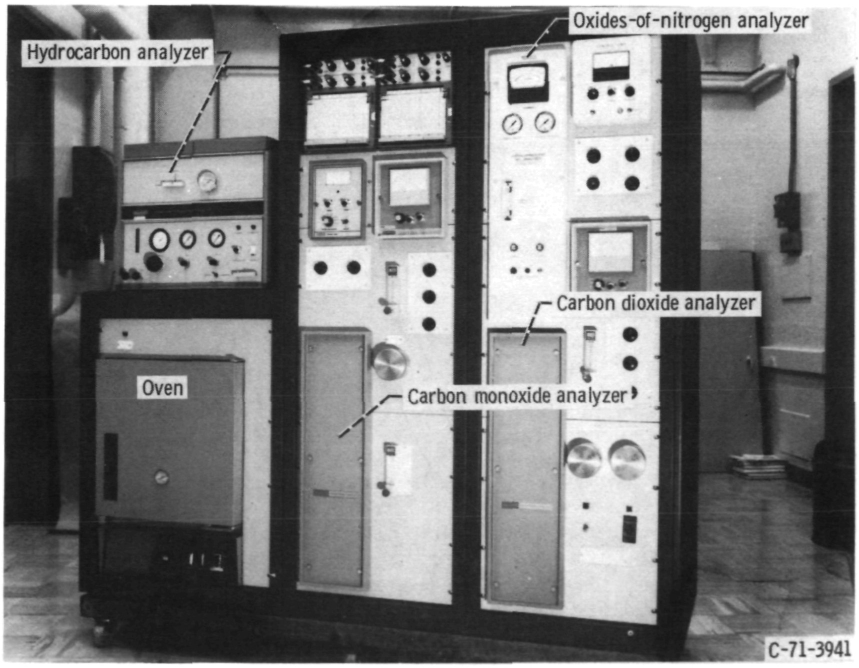

Figure 5. - Gas sampling instrument console.

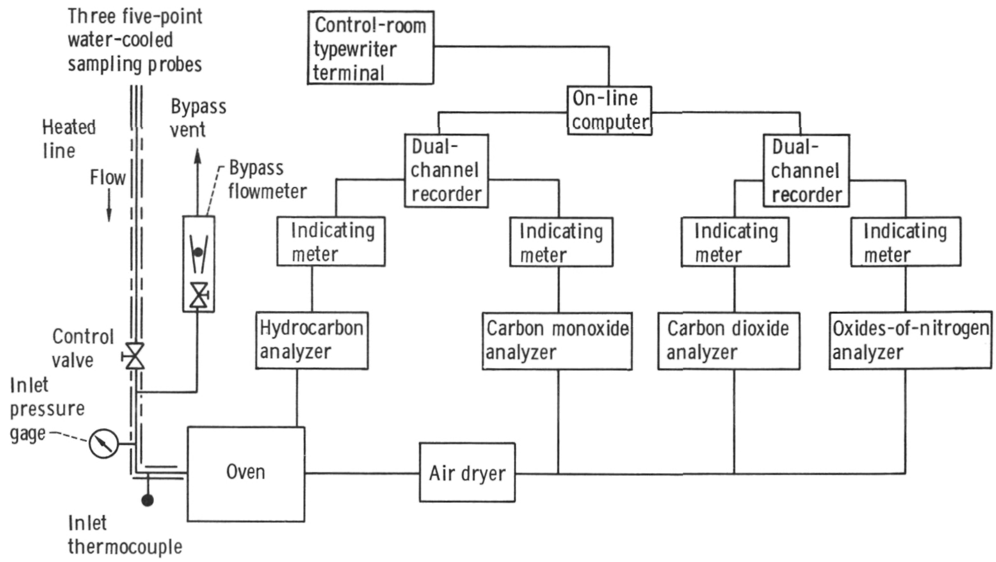

Figure 6. - Schematic diagram of gas analysis system.

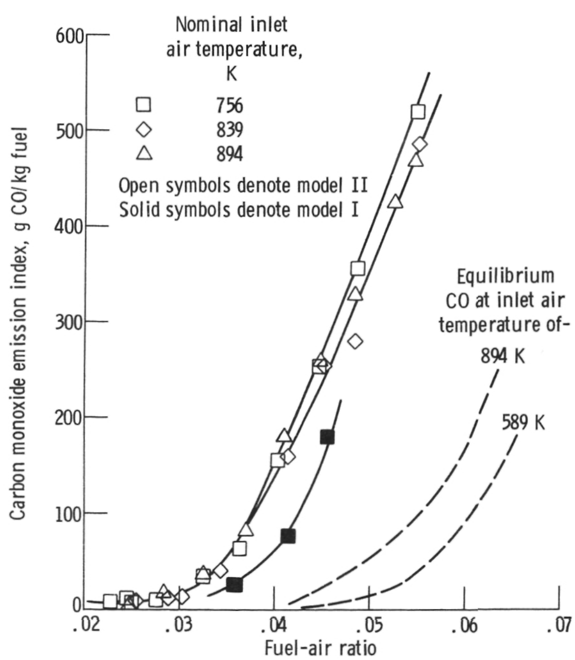

Figure 7. - Carbon monoxide emissions as function of fuel-air ratio for a stoichiometric 72-swirl-can combustor.

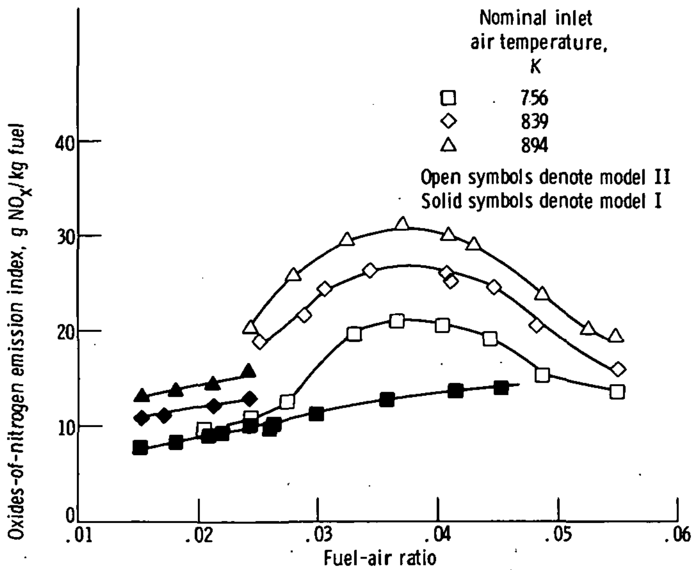

Figure 8. - Oxides-of-nitrogen emissions as function of fuel-air ratio for a stoichiometric 72-swirl-can combustor. Pressure, 6 atmospheres.

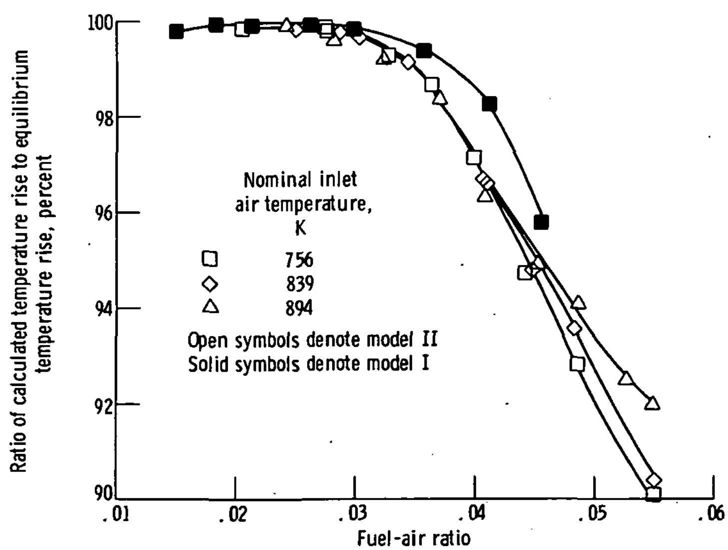

Figure 9. - Combustion efficiency as function of fuel-air ratio for a stoichiometric 72-swirl-can combustor.

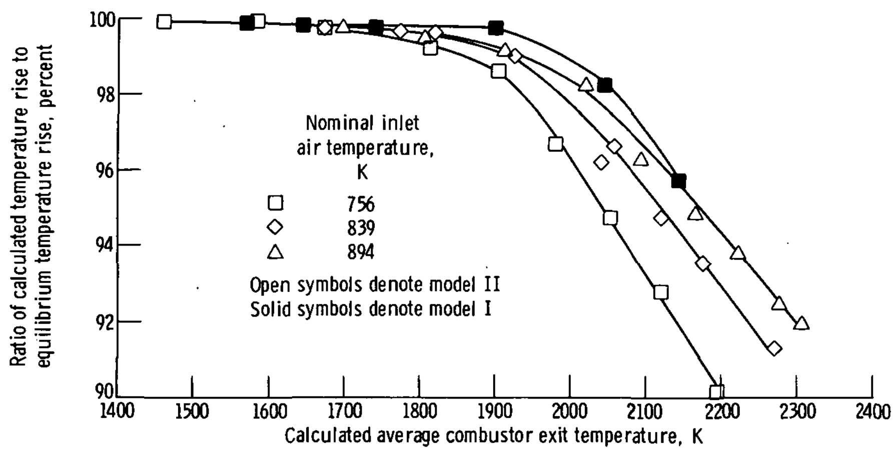

Figure 10. - Combustion efficiency as function of calculated average combustor exit temperature for stoichiometric 72-swirl-can combustor.

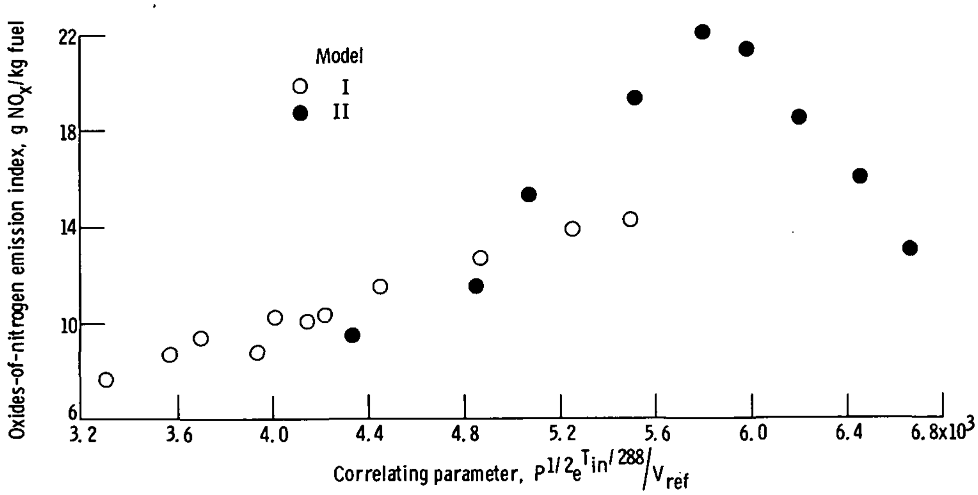

Figure 11. - Oxides-of-nitrogen emissions as function of correlating parameter for a stoichiometric 72-swirl-can combustor.

NASA-Langley, 1977 E-8317

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